Simulation of atmospheric muons in SNO

C.A. Currat, Y.D. Chan, K.T. Lesko, A.D. Marino, E.B. Norman, A.W. Poon, and R.G. Stokstad for the SNO Collaboration

The simulation of cosmic muons over a wide range of energy is of prime importance in the studies of atmospheric neutrinos. Previous work by Tagg [1] investigated the SNO capability of making a measurement of θ_{23}, based on 149 live days. To date about 700 days of data is available and a working group is preparing an extensive analysis of the atmospheric neutrino sector in SNO.

The energy spectrum of cosmics as we know it spreads over 5 decades [2], from O(100 MeV) to O(10 TeV). The typical energy of the processes originally intended to be simulated by the SNO collaboration software Snoman goes from 5 MeV (DAQ threshold) to around 20 MeV (so called *hep* events). The challenge that we met is to handle these 2 extreme scales of energy with the same software. Figure 1 (left) shows the energy spectrum of simulated cosmic muons.

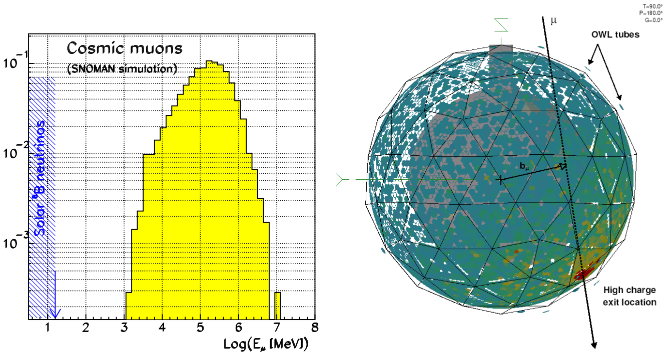

FIG. 1: (LEFT) Energy spectrum of cosmics simulated in Snoman. The blue band shows the range of energies the software was initially designed to handle (solar ^{8}B neutrinos). (RIGHT) A typical cosmic muon event reconstructed in the SNO detector. On average 2/3 of the 10^4 phototubes are hit. The total radius of the detector is $R_{\mathrm{PSUP}} =$ 890 cm.

The code has been revised and corrected to reach a stable running regime suitable for Monte Carlo production. The failure rate has been brought from a chronic 90% down to 0.5%. Although certainly not in its definitive form, the muon simulation is operational and available for physics studies [3].

The description of the muon interactions in the SNO detector (light and heavy water) includes the following processes, roughly ordered in increasing energy where they become prevalent:

- muon decay or capture (^{16}O)
- continuous loss: Cerenkov radiation
- photo-nuclear interactions (inclusive)
- exclusive spallation processes: neutron production by nuclear photodisintegration (Fig. 2, left)
- Moller scattering (ionization)
- Bremsstrahlung
- δ-rays or knock-on electrons
- pair creation (Fig. 2, right)

All the products of the reactions are tracked down until they reach rest energy or thermal energy for neutrons (1/40 eV). This means the same data structure successfully accomodates the simulation of physics processes over 15 orders of magnitude in energy in a single software.

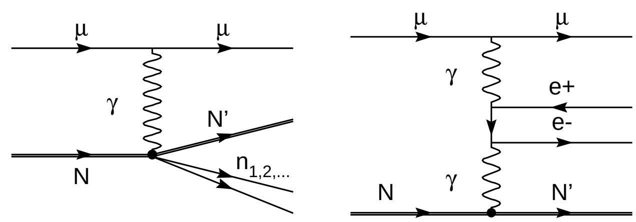

FIG. 2: (LEFT) Muon spallation process (photodisintegration) for muons with indicative energies O(10–100) GeV (RIGHT) Electron-positron pair creation in the nuclear field becomes dominant for muons with TeV energies.

Most of the execution time is spent tracking the light in the photomultiplier tubes (PMT) due to the detailed level of description necessary for the event reconstruction (see below). The largest part of the cosmics will traverse the SNO detector so it may happen that significant extra processing time is spent tracking muons in the rock surrounding the cavity. Some bypasses can be activited in order to avoid this inconvenience.

A track fitter algorithm is applied to reconstruct the incident muon track as shown on Figure 1 (right). The algorithm relies on (1) the localization of the point where the muon exits the detector, and (2) the reconstruction of the track direction using the timing of the PMTs. The efficiency of the fitter is virtually unity for impact parameters up to $0.9 \times R_{\mathrm{PSUP}}$ (corresponding to clipping path lengths greater than 8 m) and muon energies down to 4 GeV. The range at such energies becomes of the size of the detector and the occurence of stopping muons impairs the fitter performance.

Further work is being performed to still reduce the failure rate in the generation of muon events and to better characterize the fitter. The study of the spallation products following the passage of a muon is of particular interest given SNO's capability to detect neutrons. In this context the present simulation can be easily completed to assess different neutron production models, yet poorly understood.

[1] N. Tagg, Thesis, University of Guelph (2001).
[2] K. H. *et al.*, Phys. Rev. D **66**, 010001 (2002).
[3] C. Currat and J. Formaggio, conference Neutrino'04 (2004).